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Primordial Nucleosynthesis: Theory and Observations

Keith A. Olive¹, Gary Steigman², and Terry P. Walker²

¹*Theoretical Physics Institute, School of Physics & Astronomy,
University of Minnesota, Minneapolis, MN 55455*

²*Departments of Physics and Astronomy, The Ohio State University,
Columbus, OH 43210, USA*

Abstract

We review the Cosmology and Physics underlying Primordial Nucleosynthesis and survey current observational data in order to compare the predictions of Big Bang Nucleosynthesis with the inferred primordial abundances. From this comparison we report on the status of the consistency of the standard hot big bang model, we constrain the universal density of baryons (nucleons), and we set limits to the numbers and/or effective interactions of hypothetical new “light” particles (equivalent massless neutrinos).

1 Introduction

At present, the Universe is observed to be expanding [1] and filled with radiation [2] - [4] which is very cold today ($T_0 = 2.728$ K [3]). If the evolution of such a Universe is traced back in time to earlier epochs which were hotter and denser, the early Universe is a Primordial Nuclear Reactor during its first 20 minutes (≈ 1000 sec). As the early Universe expands and cools, nuclear reactions are prematurely aborted before the heavier elements can be synthesized. Only the light nuclides deuterium (D), helium-3 (^3He), helium-4 (^4He), and lithium-7 (^7Li) can be synthesized in abundances comparable to those observed (or, observable!) in a variety of astrophysical sites (*e.g.*, stars; cool, neutral gas; hot, ionized gas). Since the relative abundances of the primordially-produced nuclides depend on the density of nucleons (baryons) and on the early-Universe expansion rate, a comparison of the predicted and observed abundances provides a key test of the standard model of cosmology, as well as an indirect “measurement” of the baryon density of the Universe which is equally sensitive to dark and luminous baryons (*i.e.*, Is the early-Universe nucleon abundance consistent with that inferred today from non-BBN data?), and offers a unique probe of hypothetical new particles (beyond the standard model) whose presence would have altered the expansion rate of the early Universe (hence changing the time available for element synthesis). As one of the pillars of the standard model of Cosmology, BBN opens a unique window on the Universe.

In this review, dedicated to the memory of our friend and colleague Dave Schramm, we review the basic physics and cosmology relevant to the calculation of the primordial yields, both in the standard model and in simple extensions of the standard model. Then we compare the current predictions, based on up-to-date nuclear and weak interaction rates, with the primordial abundances inferred from observational data obtained from a variety of astrophysical sites using a variety of astronomical techniques. Since the BBN-prediction part is relatively simple and straightforward, it is the data which lies at the core of such comparisons. The good news is that the key nuclides are observed in a variety of objects using very different techniques, thus minimizing correlated systematic errors in the abundance determinations. Additional good news is that modern telescopes and detectors have provided high quality data whose statistical errors have been shrinking dramatically. The bad news is that, for most abundance determinations, the accuracy is now limited by our ignorance of possible systematic errors which are often difficult to quantify using extant data alone. Therefore, a large part of this review is devoted to the data and our assessment of the uncertainties. In this, we strive to err on the side of caution. When mutually contradictory data appears (as it does for primordial deuterium) we will explore the consequences of each option, letting the reader draw his/her own conclusion. Given the rapid pace of observational cosmology at present, the quantitative abundances derived from current data are likely ephemeral. However, it is our hope that our discussion here will set the stage for any changes new data will provide.

2 Primordial Nucleosynthesis

All that is needed to predict the primordial abundances of the light elements within the context of the standard models of cosmology and particle physics is the current temperature and expansion rate of the Universe. Then, under the assumptions that the Universe is homogeneous and isotropic and that the standard model of particle physics is the correct description of the particle content of the Universe at temperatures of order a few MeV, the predicted primordial abundances of D, ^3He , ^4He , and ^7Li depend only on the baryon density. That is, the predictions of standard BBN are uniquely determined by one parameter, η , the baryon-to-photon ratio: $\eta_{10} = 273\Omega_B h^2$ (Ω_B is the ratio of the baryon density to the critical density and the Hubble parameter is $H_0 = 100h$ km/s/Mpc; $\eta_{10} = 10^{10}\eta$).

The primordial yields of light elements are determined by a competition between the expansion rate of the Universe, the rates of the weak interactions that interconvert neutrons and protons, and the rates of the nuclear reactions that build up the complex nuclei. Neglecting the contributions of curvature and the cosmological constant, which are small in the early Universe, the expansion rate is determined by the Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 \approx \frac{8\pi}{3}G_N\rho \quad (1)$$

where R is the scale factor. For standard BBN the energy density, ρ , at the time nucleosynthesis begins (about 1 second after the Big Bang) is described by the standard model of particle physics

$$\rho = \rho_\gamma + \rho_e + N_\nu\rho_\nu \quad (2)$$

where ρ_γ , ρ_e , and ρ_ν are the energy density of photons, electrons and positrons, and massless neutrinos and anti-neutrinos (one species), respectively, and N_ν is the equivalent number of massless neutrino species which, in standard BBN, is exactly 3.

At high temperatures, neutrons and protons can interconvert via weak interactions: $n + e^+ \leftrightarrow p + \bar{\nu}_e$, $n + \nu_e \leftrightarrow p + e^-$, and $n \leftrightarrow p + e^- + \bar{\nu}_e$. As long as the interconversion rate of neutrons and protons is faster than the expansion rate, the neutron-to-proton ratio tracks its equilibrium value, exponentially decreasing with temperature. This condition holds for temperatures $T \gtrsim 1$ MeV as can be seen from a comparison of estimates of the weak rates $\Gamma_{\text{wk}} = n\langle\sigma v\rangle \sim 0(10^{-2})T^5/M_W^4$, and the expansion rate $H = (8\pi G_N\rho/3)^{1/2} \sim 5.4 T^2/M_P$, where M_W and M_P are the electroweak and Planck masses, respectively¹. Once the interconversion rate becomes less than the expansion rate, n/p effectively “freezes-out” (at about 1/6), thereafter decreasing slowly due to free neutron decay.

¹A detailed numerical calculation would find that equilibrium is maintained down to 0.8 MeV.

Although freeze-out occurs at a temperature below the deuterium binding energy, $E_B = 2.2$ MeV, the first link in the nucleosynthetic chain, $p+n \rightarrow D + \gamma$, is not effective since the photo-destruction rate of deuterium ($\propto n_\gamma e^{-E_B/T}$) is much larger than the production rate ($\propto n_B$) due to the large photon-to-baryon ratio ($\gtrsim 10^9$). As soon as deuterium becomes stable against photodissociation (~ 80 keV) neutrons are bound up into ${}^4\text{He}$ with an efficiency of 99.99%, driven by the stability of the ${}^4\text{He}$ nucleus. By this time, n/p has dropped to $\sim 1/7$, and simple counting yields an estimated ${}^4\text{He}$ mass fraction

$$Y_P \approx \frac{2(n/p)}{[1 + (n/p)]} = 0.25. \quad (3)$$

In addition, the large binding energy of ${}^4\text{He}$ insures that its primordial abundance is relatively insensitive to the nuclear reaction rates (which increase with increasing baryon density (η)). D (and ${}^3\text{He}$) is burned to get to complex nuclei and thus its abundance decreases rapidly with increasing η , making D the perfect baryometer (see section 3.1). At low η , ${}^7\text{Li}$ is destroyed by protons with an efficiency that increases with η , while at relatively high η , ${}^7\text{Be}$ (the dominant route to ${}^7\text{Li}$ by subsequent electron capture) is produced more efficiently with increasing η . Hence the “Li valley” in a ${}^7\text{Li}$ vs. η plot. Increasing Coulomb barriers and a lack of stable nuclei at $A = 5$ and 8 cause standard BBN to struggle to produce ${}^7\text{Li}$ and be even less effective beyond that.

In Figures 1 – 3, the primordial abundances predicted by standard BBN are shown as a function of η . The width of each curve reflects the 2σ uncertainty in the predictions that results from a Monte Carlo analysis of uncertainties in the neutron lifetime and nuclear reaction rates [5]. The neutron lifetime was taken to be $\tau_n = 887 \pm 2$ seconds². At $\eta = 5 \times 10^{-10}$ the fractional uncertainties due to 2σ experimental errors are 0.4% for Y, 15% for D or ${}^3\text{He}$, and 42% for ${}^7\text{Li}$ if the errors in the cross sections from Smith *et al.* [7] are used. We note that recent work [8], based on a preliminary reanalysis and update of the relevant reaction cross sections, claims smaller uncertainties in D and ${}^7\text{Li}$ by roughly a factor of two. The robustness of the BBN predictions is directly related to the fact that, for the most part, the astrophysical S-factors are measured at energies relevant to the BBN environment.

The fractional uncertainty in the predicted mass fraction of ${}^4\text{He}$ due to experimental errors in the reaction rates is, for the range of nucleon density of interest, almost entirely due to the uncertainty in the neutron lifetime (which translates into an overall uncertainty in the weak interconversion rates). In the last few years considerable effort has gone into understanding the theoretical uncertainty in the predicted abundance of ${}^4\text{He}$ due to the treatment of the weak interaction rates. The BBN code used for the results presented in Walker *et al.* (WSSOK) [9] was basically the ‘Wagoner Code’ [10] (updated first by Yang [11, 12, 13]) with modifications by Walker[14] to include zero and finite-temperature radiative corrections and Coulomb corrections to the weak rates

²The current world average is $\tau_n = 886.7 \pm 1.9$ [6] leading to predictions indistinguishable from those displayed.

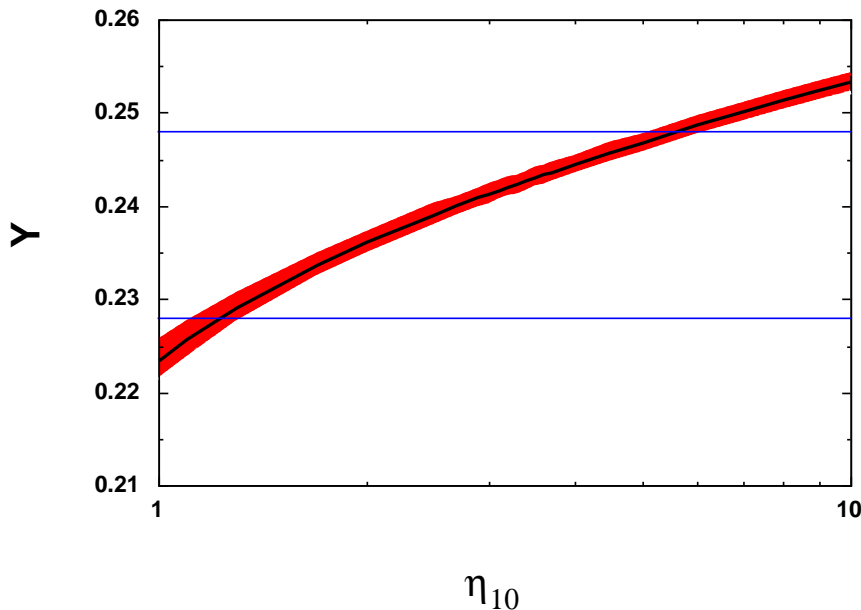


Figure 1: The predicted ${}^4\text{He}$ abundance (solid curve) and the 2σ theoretical uncertainty [5]. The horizontal lines show the range indicated by the observational data.

(as described in Dicus *et al.* [15]). Subsequent modifications included an update and enlargement of the nuclear network by Thomas in TSOFF [16]. Kernan re-examined the code [17], updating the TSOFF code to include finite nucleon mass effects (as described in Seckel [18] and Lopez, Turner, and Gyuk [19]) and finding a relatively large time-step error. He also estimated the uncertainty in the ${}^4\text{He}$ mass fraction due to choice of finite-temperature prescription and non-equilibrium effects in the neutrino sector to be $\sim 10^{-4}$. Kernan’s recommendation was, to a level of accuracy of a few parts in 10^4 , to simply use the Y_P found in the ‘WSSOK Code’ and add 0.003. This was adopted in Hata *et al.* [5] to yield $Y_P = 0.2467$ (theoretical uncertainty of a few parts in 10^{-4}) at $\eta = 5 \times 10^{-10}$ and $\tau_n = 887$ seconds. With several versions of the BBN code floating around, no one but the owners (and sometimes not even they) knew how the various “ Y_P -corrections” were handled and no one had built an independent version of the code that contained all these corrections in a self-consistent way. Lopez and Turner [20] have recently done just that. Starting from scratch, including all the effects mentioned above, and adding order- α QED corrections (as described by Heckler [21]) and detailed non-equilibrium neutrino effects (as described by Dodelson and Turner [22]) they find: $Y_P = 0.2460 \pm 0.0002$ (theory) at $\eta = 5 \times 10^{-10}$ and $\tau_n = 885.4$ seconds (if they use $\tau_n = 887$ seconds they find $Y_P = 0.2467$ (Lopez, Private Communication to G.S.)). Indeed, over the entire range $1 \leq \eta_{10} \leq 10$, the difference in predicted ${}^4\text{He}$ mass fraction between our

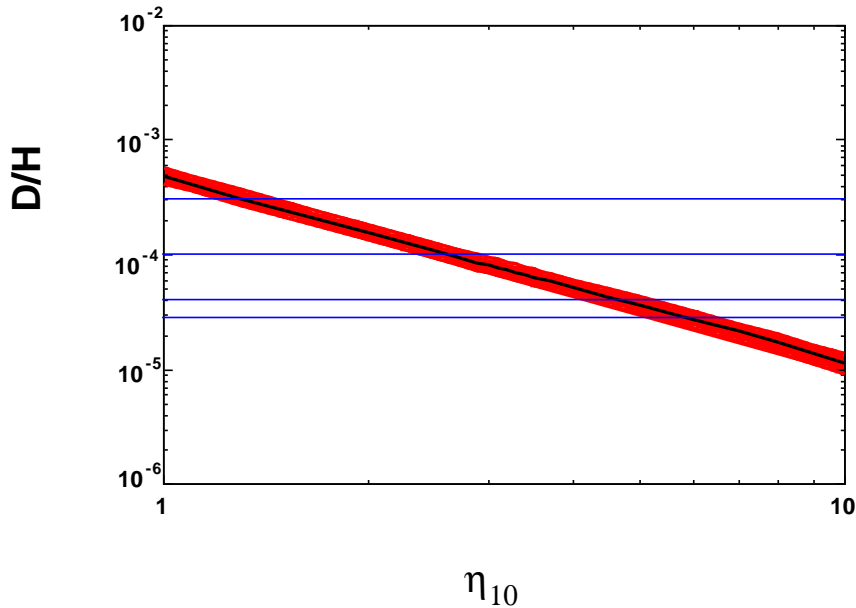


Figure 2: The predicted D/H abundance (solid curve) and the 2σ theoretical uncertainty [5]. The horizontal lines show the range indicated by the observational data for both the high D/H (upper two lines) and low D/H (lower two lines).

code and the Lopez/Turner code is 0.0001 ± 0.0001 .

3 From Observations To Primordial Abundances

To test the standard model it is necessary to confront the predictions of BBN with the primordial abundances of the light nuclides which are not “observed”, but are inferred from observations. The path from observational data to primordial abundances is long and twisted and often fraught with peril. In addition to the usual statistical and insidious systematic uncertainties, it is necessary to forge the connection from “here and now” to “there and then”, *i.e.*, to relate the derived abundances to their primordial values. It is fortunate that each of the key elements is observed in different astrophysical sites using very different astronomical techniques and that the corrections for chemical evolution differ and, even more important, can be minimized. For example, deuterium is mainly observed in cool, neutral gas (H I regions) via resonant UV absorption from the ground state (Lyman series), while radio telescopes allow helium-3 to be studied via the analog of the 21 cm line for $^3\text{He}^+$ in regions of hot, ionized gas (H II regions). Helium-4 is probed via emission from its optical recombination lines in H II regions. In contrast, lithium is observed in the absorption

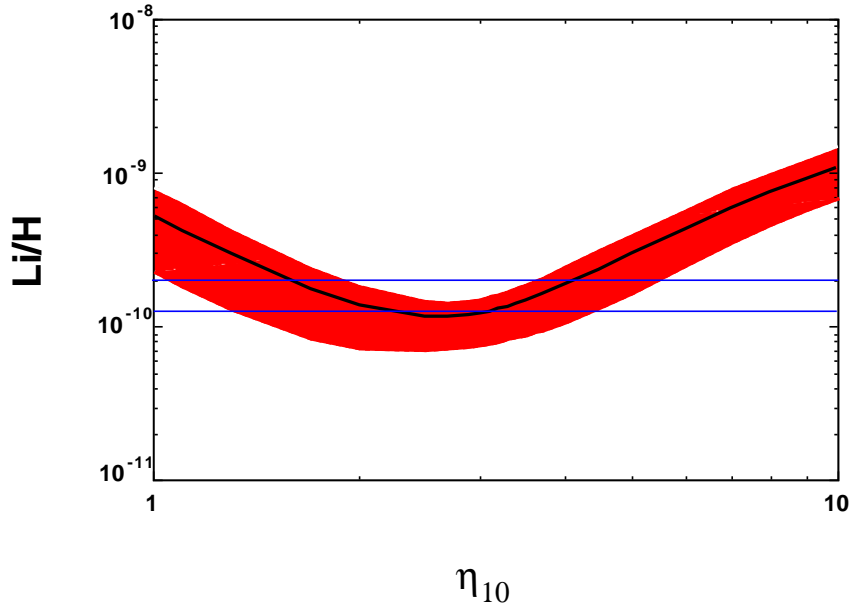


Figure 3: The predicted ${}^7\text{Li}$ abundance (solid curve) and the 2σ theoretical uncertainty [5]. The horizontal lines show the range indicated by the observational data.

spectra of hot, low-mass halo stars. With such different sites, with the mix of absorption/emission, and with the variety of telescopes involved, the possibility of correlated errors biasing the comparison with the predictions of BBN is unlikely. This favorable situation extends to the obligatory evolutionary corrections. For example, although until recently observations of deuterium were limited to the solar system and the Galaxy, mandating uncertain corrections to infer the pregalactic abundance, the Keck and Hubble Space telescopes have begun to open the window to deuterium in high-redshift, low-metallicity, nearly primordial regions (Lyman- α clouds). Observations of ${}^4\text{He}$ in low-metallicity ($\sim 1/50$ of solar) extragalactic H II regions permit the evolutionary correction to be reduced to the level of the statistical uncertainties. The abundances of lithium inferred from observations of the very metal-poor halo stars (one-thousandth of solar and even lower) require almost no correction for chemical evolution. On the other hand, the status of helium-3 is in contrast to that of the other light elements. Although all prestellar D is converted to ${}^3\text{He}$ during pre-main sequence evolution, ${}^3\text{He}$ is burned to ${}^4\text{He}$ and beyond in the hotter interiors of most stars, while it survives in the cooler exteriors. For lower mass stars a greater fraction of the prestellar ${}^3\text{He}$ is expected to survive and, indeed, incomplete burning leads to the buildup of ${}^3\text{He}$ in the interior which may, or may not, survive to be returned to the interstellar medium [23]. In fact, some planetary nebulae have been observed to be highly enriched in ${}^3\text{He}$, with abun-

dances ${}^3\text{He}/\text{H} \sim 10^{-3}$ [24]. Although such high abundances are expected in the remnants of low mass stars [23, 25], if all stars in the low mass range produced comparable abundances, we would expect solar and present ISM abundances of ${}^3\text{He}$ to greatly exceed their observed values [25, 26, 27]. It is therefore necessary that at least *some* low mass stars are net destroyers of ${}^3\text{He}$. For example, there could be “extra” mixing below the convection zone in these stars when they are on the red giant branch [28, 29, 30]. Given such possible complicated histories of survival, destruction, and production, it is difficult to use the current Galactic and solar system data to infer (or, even bound) the primordial abundance of ${}^3\text{He}$. For this reason, we will not consider ${}^3\text{He}$ any further in this review.

The generally favorable observational and evolutionary state of affairs for the nuclides produced during BBN is counterbalanced by the likely presence of systematic errors which are difficult to quantify and, in some cases, by a woefully limited data set. As a result, although cosmological abundance determinations have taken their place in the current “precision” era, it is far from clear that the present abundance determinations are “accurate”. Thus, the usual *caveat emptor* applies to any conclusions drawn from the comparison between the predictions and the data. With this caution in mind we survey the current status of the data to infer “reasonable” ranges for the primordial abundances of the key light elements.

3.1 Deuterium

Deuterium is the ideal baryometer. As we have noted above the BBN-predicted D/H ratio is a strong function of the baryon-to-photon ratio η . A determination of the primordial abundance to 10%, leads to an η determination accurate to $\sim 6\%$. Furthermore, since deuterium is burned away whenever it is cycled through stars, and there are no astrophysical sites capable of producing deuterium in anywhere near its observed abundance [31], any observed D-abundance provides a *lower* bound to its primordial abundance. Thus, without having to correct for Galactic evolution, the deuterium abundance inferred from UV observations of the local interstellar medium (LISM) [32], $\text{D}/\text{H} = (1.5 \pm 0.1) \times 10^{-5}$ (unless otherwise noted, observational errors are quoted at 1σ), bounds the primordial abundance from below and the baryon-to-photon ratio from above [33]. This value represents an average along 12 lines of sight in the LISM. Although they are not directly relevant to BBN, it is interesting to note that there have been several reports [34, 35] of a dispersion in ISM D/H abundances. It is not clear whether such variations are related to those inferred for the ${}^3\text{He}/\text{H}$ abundances in Galactic H II regions [36].

Solar system observations of ${}^3\text{He}$ permit an indirect determination of the pre-solar system deuterium abundance (Geiss & Reeves 1972). This estimate of the Galactic abundance some 4.5 Gyr ago, $\text{D}/\text{H} = (2.1 \pm 0.5) \times 10^{-5}$ (Geiss & Gloeckler 1998), while having larger uncertainty, is consistent with the LISM value. There has also been a recent measurement of deuterium in the atmosphere of Jupiter using the Galileo Probe Mass Spectrometer [37], which finds $\text{D}/\text{H} = (2.6 \pm 0.7) \times 10^{-5}$.

To further exploit the solar system and/or LISM deuterium determinations to constrain/estimate the primordial abundance would require corrections for the Galactic evolution of D. Although the simplicity of the evolution of deuterium (only destroyed) suggests that such correction might be very nearly independent of the details of specific chemical evolution models, large differences remain between different estimates [38, 39]. It is therefore fortunate that data on D/H in high-redshift, low-metallicity Lyman- α absorbers has become available in recent years [40]–[45]. It is expected that such systems still retain their original, primordial deuterium, undiluted by the deuterium-depleted debris of any significant stellar evolution. That’s the good news. The bad news is that, at present, there are D-abundance determinations claimed for only four such systems and that the abundances inferred for two of them appear to be inconsistent with the abundances determined in the other two. Here is a prime example of “precise” but possibly inaccurate cosmological data. There is a serious obstacle inherent to using absorption spectra to measure the deuterium abundance since the isotope-shifted deuterium lines are indistinguishable from velocity-shifted hydrogen. Such “interlopers” may have been responsible for some of the early claims [40] of a “high” deuterium abundance [46]. Data reduction errors may have been the source of another putative high-D system. At present it seems that only three good candidates for nearly primordial deuterium have emerged from ground- and space-based observations.

The absorption system at $z = 3.572$ towards Q1937-1009 was first studied by Tytler, Fan & Burles [41] who derived a low $D/H = (2.3 \pm 0.3 \pm 0.3) \times 10^{-5}$. Since an uncertain hydrogen column density, due to the saturated Lyman series profiles, was the largest source of uncertainty [47], new, high quality, low-resolution spectra were obtained [42], which, along with a new fitting procedure led to a revised abundance: $D/H = (3.3 \pm 0.3) \times 10^{-5}$; notice the rather poor overlap with the original abundance. The $z = 2.504$ absorption system towards Q1009+2956 provides another potentially accurate D-abundance determination [43] $D/H = (4.0 \pm 0.7) \times 10^{-5}$. There are two other systems studied by Burles & Tytler (1998) whose derived D-abundances are consistent with these two, but whose uncertainties are much larger. The weighted mean of the two accurate D-abundance determinations leads to a 95% confidence range: $2.9 \times 10^{-5} \leq D/H \leq 4.0 \times 10^{-5}$. We adopt this range in our comparisons with the BBN predictions.

We note that Levshakov, Kegel & Takahara ([48], LKT) have used the data in [41] for the $z = 3.572$ system towards Q1937-1009, but with a different model for the velocity distribution of the absorbing gas, to derive a (95% confidence) range $3.5 \times 10^{-5} \leq D/H \leq 5.2 \times 10^{-5}$, which argues for a slightly higher abundance than suggested by the Burles & Tytler [42] range. These same authors also used their model to reanalyze the Burles & Tytler [43] data for Q1009+2956 [49] and they derive a 95% estimated range of $2.9 \times 10^{-5} \leq D/H \leq 4.6 \times 10^{-5}$, now in excellent agreement with the Burles & Tytler [43] value for this system. Recently, Levshakov, Tytler & Burles ([50], LBT) have joined forces to apply this different model to a reanalysis of the $z = 2.504$ absorption system towards Q1009+2956, finding a consistent but slightly higher range (68%): $D/H \simeq (3.5 - 5.0) \times 10^{-5}$.

Although deuterium in the two high-redshift absorbers is consistent with a primordial abundance in the range $2.9 \times 10^{-5} \leq D/H \leq 4.0 \times 10^{-5}$ (or slightly higher accounting for the LKT and LBT analyses of the same data), the deuterium abundance derived for the one low-redshift absorber, the $z = 0.701$ system towards Q1718+4807 observed with the GHRS on HST is significantly different. This data was first analyzed by Webb *et al.* [44] who derived a very high deuterium abundance: $D/H = (20 \pm 5) \times 10^{-5}$. In contrast, LKT [51] using the same data but their model for the velocity distribution of the absorbing gas, derive an abundance closer to those for the high-redshift absorbers: $4.1 \times 10^{-5} \leq D/H \leq 4.7 \times 10^{-5}$. Recently, Tytler *et al.* [45] use new Keck spectra to supplement the data from HST to derive a 95% range: $8 \times 10^{-5} \leq D/H \leq 57 \times 10^{-5}$, consistent with the Webb *et al.* (1997) estimate. Clearly the high-D abundance inferred from some analyses of this system are inconsistent with the low-D abundances derived from the other two, higher-redshift systems. The sense of the discrepancy is puzzling since it is expected that the deuterium abundance should only decrease with time (decreasing redshift). If, in fact, the high abundance is representative of the primordial value, then the other two absorbers should consist of gas most of which has been cycled through stars. The high redshifts and low metallicities of these systems suggest this is unlikely. If high D-abundances at high- z and low- Z are common, many systems like Q1718+4807 should present themselves for analysis. Tytler (1998) has argued that the absence (so far) of very many possible candidates suggests that either the abundance determination in the Q1718+4807 absorber is unreliable, or the Q1718+4807 absorber is anomalous.

In anticipation of new data which may resolve this conundrum, we prefer to keep our options open and discuss the consequences of either of two (mutually exclusive) possibilities. For the low-D case we use the two high- z systems and adopt the Burles-Tytler 95% range: $2.9 \times 10^{-5} \leq D/H \leq 4.0 \times 10^{-5}$. For the high-D case we adopt the range: $1 \times 10^{-4} \leq D/H \leq 3 \times 10^{-4}$ based on the 2σ range of Webb *et al.* [44]. With account for the uncertainty in the BBN-predicted D-abundance at fixed η , the lower bound to primordial D/H for the low-D case leads to an upper bound to η of: $\eta_{10} \leq 6.3$, while the upper bound on D/H leads to a lower bound on η of: $\eta_{10} \geq 4.2$. For the high-D option, the corresponding range in η is: $1.2 \leq \eta_{10} \leq 2.8$. In making these estimates we have been “overly generous” in the sense that the η values correspond to the “ 2σ ” uncertainties in the observational data and the “ 2σ ” uncertainties in the BBN predictions.

3.2 Helium-4

As the second most abundant nuclide in the Universe (after hydrogen), the abundance of ^4He can be determined to high accuracy at sites throughout the Universe. To minimize the uncertainty inherent in any correction for the debris of stellar evolution, it is sensible to concentrate on the data from low-metallicity, extragalactic H II regions [52]-[59]. Since each data set contains of order 40 regions, various analyses achieve statistical uncertainties in their estimate of the

primordial helium mass fraction ≤ 0.003 (or, $\leq 1\%$). Further, since the most metal-poor of these regions have metallicities of order $1/50 - 1/30$ of solar, the extrapolation from the lowest metallicity regions to truly primordial introduces an uncertainty no larger than the statistical error. Although ^4He has already entered the era of “precision cosmology”, difficult to constrain systematic uncertainties dominate the error budget. For example, using published data for 40 low-metallicity regions (excluding the suspect NW region of IZw18), Olive & Steigman (OS) [55] find: $Y_P = 0.234 \pm 0.003$ based on the data in [52, 53]. In contrast, from an independent data set of 45 low-metallicity regions with only slight overlap with that of OS, Izotov & Thuan (IT) [57] infer $Y_P = 0.244 \pm 0.002$. Clearly these results are statistically inconsistent. Several contributions to this discrepancy can be identified. Since the intensity of the helium recombination emission lines can be enhanced by collisional excitation [58], corrections for collisional excitation are mandatory. In [54, 57] an attempt was made to use helium-line data alone (5 lines) to make this correction, in contrast to the traditional approach using information on the electron density derived from non-helium line data (see Skillman, Terlevich & Terlevich [60] for a discussion). It is of great value that Izotov *et al.* [54] (ITL) and IT also analyze their data according to the traditional approach since this permits an estimate of the effect of their approach on the inferred primordial abundance. Using their data for 44 regions analyzed similarly to the data employed in OS, they would have derived $Y_P = 0.241 \pm 0.002$, reducing the discrepancy between OS and IT. Another source of systematic difference between the two analyses can be identified. By relying on helium (and hydrogen) recombination lines, any neutral helium (or hydrogen) present in the H II regions is invisible and must be corrected for. Since any such correction will be model dependent and uncertain, Pagel *et al.* [52] restricted their attention to H II regions of “high excitation” for which this correction should be minimized. As a result they (and most of the data utilized by OS) make no ionization correction. In contrast ITL, through a misreading of published models of H II regions, make a correction for neutral helium while ignoring the (predicted) larger correction for neutral hydrogen in regions ionized by hot stars (metal-poor stars are hotter than the corresponding solar metallicity stars). Skillman, Terlevich & Terlevich [60] estimate the size of this correction to be of order 1% ($\Delta Y_P \approx -0.002$), further reducing the discrepancy between the IT and OS Y_P estimates to ≈ 0.005 rather than the original 0.010. Although IT eliminate the erroneous ionization correction from ITL in their more recent work, they actually derive a *higher* helium abundance. IT remark that this may be due to the higher temperatures in their new regions (compared to the ITL data set).

At present potentially the most significant systematic uncertainty affecting the derived primordial abundance of helium appears to be that due to possible underlying stellar absorption (ITL; IT; Skillman, Terlevich & Terlevich [60]). It has become clear that the helium abundance determination in the NW region of IZw18 is likely contaminated by such absorption, resulting in an underestimate of the true abundance. Other regions in the OS and Olive, Skillman & Steigman [56] (OSS) data sets may suffer similar contamination, biasing their

estimate of the primordial helium abundance to values which may be too low. In contrast, ITL/IT select their regions on the basis of the strength of the helium lines, avoiding those weak-lined regions which may be contaminated by underlying stellar absorption. If, indeed, they have been successful in avoiding this systematic error, their higher abundance estimate may be closer to the true value. But, through such selection they have run the risk of introducing a bias against finding low helium abundances.

It is clearly crucial that high priority be assigned to using the H II region observations themselves to estimate/avoid the systematic errors due to underlying stellar absorption, to collisional excitation and, to corrections for neutral helium and/or hydrogen. Until then, the error budget for Y_P is likely dominated by systematic rather than statistical uncertainties and it is difficult to decide between OS (and OSS) and IT. When account is taken of systematic uncertainties, they may in fact be consistent with each other. Therefore, in what follows, we will adopt a generous “95%” range of $0.228 \leq Y_P \leq 0.248$ (*cf.* [59]).

3.3 Lithium-7

Cosmologically interesting lithium is observed in the Pop II halo stars [61]–[64] which are so metal-poor they provide a sample of more nearly primordial material than anything observed anywhere else in the Universe; the most metal-poor stars have less than one-thousandth the solar metallicity. Of course these halo stars are the oldest stars in the Galaxy and, as such, have had the most time to modify their surface abundances. So, although any correction for evolution modifying the lithium abundance may be smaller than the statistical uncertainties of a given measurement, the systematic uncertainty associated with the dilution and/or destruction of surface lithium in these very old stars could dominate the error budget. Additional errors are associated with the modeling of the surface layers of these cool, low-metallicity, low-mass stars, such as those connected with stellar atmosphere models and the temperature scale. It is also possible that some of the observed Li is non-primordial, (*e.g.*, that some of the observed Li may have been produced by spallation or fusion in cosmic-ray collisions with gas in the ISM [65, 66]).

There now exists a very large data set of lithium abundances measured in the warmer ($T > 5800K$), metal-poor ($[Fe/H] < -1.3$) halo stars. Within the errors, these abundances define a plateau (the “Spite-plateau”) in the lithium abundance – metallicity plane. Depending on the choice of stellar-temperature scale and model atmosphere the abundance level of the plateau is: $A(Li) \equiv 12 + \log(Li/H) = 2.2 \pm 0.1$, with very little intrinsic dispersion around this plateau value (*e.g.*, [62]). This small dispersion provides an important constraint on models which attempt to connect the present surface lithium abundances in these stars to the original lithium abundance in the gas out of which these stars were formed some 10 – 15 Gyr ago. “Standard” (*i.e.*, non-rotating) stellar models predict almost no lithium depletion and, therefore, almost no dispersion about the Spite-plateau [67].

Early work on mixing in models of rotating stars was very uncertain, predict-

ing as much as an order of magnitude ${}^7\text{Li}$ depletion. Recently, Pinsonneault *et al.* [68], building on progress in the study of the angular momentum evolution of low-mass stars [69], constructed stellar models which reproduce the angular momentum evolution observed for low-mass open cluster stars, and have applied these models, normalized to the open cluster data and to the observed solar lithium depletion, to the study of lithium depletion in main sequence halo stars. Using the distribution of initial angular momenta inferred from young open clusters for the halo stars leads to a well-defined lithium plateau with modest scatter and a small population of “outliers” (overdepleted stars) which is consistent with the data. Consistency with the solar lithium, with the open cluster stars, and with the (small) dispersion in the Spite-plateau may be achieved for depletion factors between 0.2 dex and 0.4 dex [68].

The amount of depletion can also be limited [70, 71, 72] by observations of ${}^6\text{Li}$ [73]. If the original ${}^6\text{Li}$ in halo stars is assumed to be as high as the solar value, an upper bound of 0.4 dex ${}^7\text{Li}$ depletion in rotational models is obtained from ${}^6\text{Li}$ data [68]. Recent analysis [71] suggests a more stringent (*albeit* model dependent) ${}^7\text{Li}$ depletion limit of 0.2 dex based on constraints on the low metallicity ($[\text{Fe}/\text{H}] \approx -2.3$) production of ${}^6\text{Li}$. Clearly ${}^6\text{Li}$ plays a vital role when it comes to constraining ${}^7\text{Li}$ depletion – the key issue to be resolved is the evolution of ${}^6\text{Li}$ in low metallicity environments and the data required are the simultaneous observations of the isotopes of Li, Be, and B in low metallicity halo stars.

Very recently, Ryan, Norris & Beers (RNB) [64] have presented data for 23 very metal-poor ($[\text{Fe}/\text{H}] \lesssim -2.5$) field turnoff stars, chosen specifically to lie in a limited range of metallicity so as to facilitate the study of the dispersion in the Spite plateau. Although the limited data set subjects any conclusions to the uncertainties due to small number statistics, these data confirm previous suggestions [62] that there is very little dispersion about the plateau abundance. RNB claim evidence for a slope in the $A(\text{Li})$ vs $[\text{Fe}/\text{H}]$ data (an increase of Li with Fe). If real, this suggests that not all of the inferred lithium is primordial. In a recent analysis [74], it is argued that 0.04 – 0.2 dex of the observed $A(\text{Li})$ could be post-primordial in origin. On the basis of the very small residual dispersion after accounting for the trend in $A(\text{Li})$ with $[\text{Fe}/\text{H}]$, and with some “outliers” removed, RNB argue that their data (which may be statistics limited) is consistent with no dispersion and for an upper limit on the lithium depletion of 0.1 dex. As discussed in [68], the fraction of “outliers” is crucial for constraining rotationally mixed models. As of this writing most, if not all, evidence points to a rather limited depletion of no more than 0.2 dex, either in standard stellar models or in those including rotation.

To err on the side of caution, we adopt a central value for the plateau abundance of $A(\text{Li}) = 2.2$ and we choose a $\sim 2\sigma$ range of ± 0.1 dex so that our adopted “95%” range is: $2.1 \leq A(\text{Li}) \leq 2.3$. If depletion is absent, this range is consistent with the lithium “valley”. For depletion ≥ 0.2 dex, the consistent lithium abundances bifurcate and move up the “foothills”, although a non-negligible contribution from post-primordial lithium could move the primordial abundance back down again.

4 Confrontation Of BBN Predictions And Observational Data

In the context of the “standard” model (three families of light or massless, two-component neutrinos), the predictions of BBN depend on only one free parameter, the nucleon-to-photon ratio η . Recalling that for $T_0 = 2.728$ K, $\eta_{10} = 273\Omega_B h^2$, the baryon inventory of Persic & Salucci [75] may be used to set a very conservative lower bound, $\eta_{10} \geq 0.25$. From constraints on the total mass density and the Hubble parameter, the extreme upper bound on η could be nearly three orders of magnitude larger. Over this large range in cosmologically “interesting” nucleon abundance, the predicted abundance of deuterium changes by more than eight orders of magnitude, from more than several parts in 10^3 to less than a part in 10^{11} as can be seen in Figure 4, where the BBN predictions are shown over a wide range in η . Over this same range in nucleon abundance, the lithium abundance varies from a minimum around 10^{-10} to a maximum some two orders of magnitude larger, while the predicted primordial helium mass fraction is anchored between 0.2 and 0.3. Even the ^3He abundance, which we have set aside due to its uncertain Galactic evolution, varies from much higher than observed ($\geq 10^{-4}$) to much less than observed ($\approx 10^{-6}$). The key test of the standard, hot, big bang cosmology is to ask if there exists a unique value (range) of η for which the predictions of the primordial abundances are consistent with the light element abundances inferred from the observational data. Since we have allowed for the possibility that one of the two current estimates of primordial deuterium from extragalactic, absorption studies could reflect the true abundance of primordial deuterium, our test must be done in two parts. Monte Carlo techniques have proven to be a useful tool in the analysis of the concordance between the BBN predictions and the observationally determined abundances of the light elements [5, 7] [76]-[79]. However, since for the purpose of this review we have taken a broad brush approach to the observational data, we limit ourselves to a simpler, more semi-quantitative discussion of this comparison.

4.1 Low Deuterium

From the two well-observed high-redshift absorption-line systems, we have adopted the Burles and Tytler 95% estimate for the primordial-D abundance: $(\text{D}/\text{H})_{\text{P}} = 2.9 - 4.0 \times 10^{-5}$. With allowance for the (2σ) uncertainties in the BBN-predicted abundance (see Fig. 2), the consistent range of η is quite narrow: $\eta_{10} = 4.2 - 6.3$. For this range in nucleon-to-photon ratio, the primordial lithium abundance is predicted (with account for the 2σ uncertainties in the prediction) to lie in the range: $A(\text{Li})_{\text{BBN}} = 2.1 - 2.8$. In our discussion of the status of the lithium observational data we identified a range for its primordial abundance which has significant overlap with this predicted range (see Fig. 3): $A(\text{Li})_{\text{P}} = 2.1 - 2.3$. Thus, the D-constrained range of $\eta_{10} = 4.2 - 6.3$, is consistent with the inferred primordial abundance of lithium, even allowing for ~ 0.2 dex stellar destruction

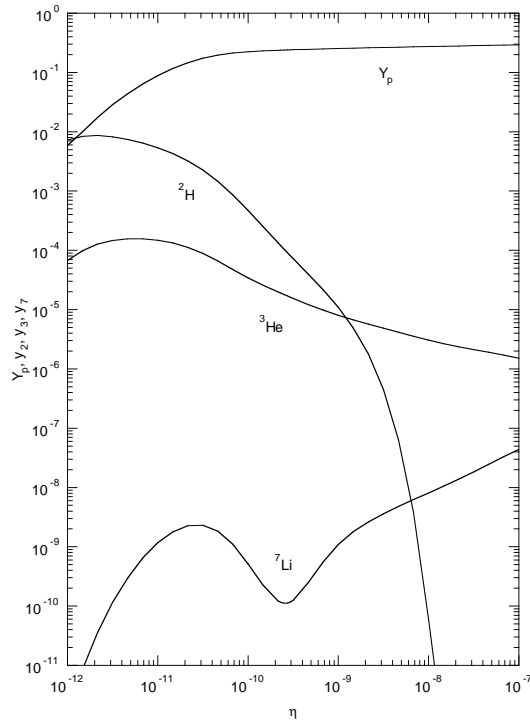


Figure 4: The predicted abundances as a function of η .

and/or galactic production. So far, so good. What of primordial helium? Over this limited range in η , the predicted helium mass fraction varies but little. With account for the (small) uncertainty in the prediction (dominated for this range in η by the uncertainty in the neutron lifetime): $Y_{\text{BBN}} = 0.244 - 0.250$. This range in the predicted primordial helium mass fraction, although on the high side, has significant overlap with the range inferred from observations of the low-metallicity, extragalactic H II regions: $Y_{\text{P}} = 0.228 - 0.248$. For “low-D”, the standard model passes this key cosmological test. For η_{10} in the narrow range from 4.2 to 6.3, the predicted and observed abundances of deuterium, helium-4 and lithium-7 are in agreement (and, the predicted abundance of helium-3 is consistent with the abundances inferred for the interstellar medium and in the presolar nebula).

4.2 High Deuterium

If, instead, the high abundance of deuterium derived from HST and Keck observations of one relatively low-redshift absorption-line system is truly representative of the primordial deuterium abundance, a different range for the nucleon-to-photon ratio is identified: $\eta_{10} = 1.2 - 2.8$ (see Fig. 2). The predicted primordial abundance of lithium for this range is $A(\text{Li}) = 1.9 - 2.7$ revealing virtually perfect agreement with the abundance derived from the very metal-poor halo stars in the Spite plateau. Over this same η range, the predicted helium mass fraction varies from $Y_{\text{BBN}} = 0.225$ to 0.241 . Here, too, the prediction is in excellent agreement with the observed abundance range. Thus, for “high-D” as well, the standard model passes this key cosmological test.

4.3 Consistency With Non-BBN Estimates?

Having established the internal consistency of primordial nucleosynthesis in the standard model, it is necessary to proceed to the next key test. Does the nucleon abundance inferred from processes which occurred during the first thousand seconds of the evolution of the Universe agree with estimates/bounds to the nucleon density in the present Universe?

It is a daunting task to attempt to inventory the baryons in the Universe. Since many (most?) baryons may be “dark”, such approaches can best set *lower* bounds to the present ratio of baryons-to-photons. In their inventory of visible baryons, Persic & Salucci [75] estimate for the baryon density parameter: $\Omega_{\text{B}} \approx 0.0022 + 0.0015h_{50}^{-1.3}$, where h_{50} is the Hubble parameter in units of 50 km/sec/Mpc. For a lower bound of $H_0 \geq 50$ km/sec/Mpc, this corresponds to a lower bound on η of: $\eta_{10} \geq 0.25$, entirely consistent with our BBN estimates. More recently, Fukugita, Hogan & Peebles [80] have revisited this question. With subjective, but conservative estimates of the uncertainties, their lower bound to the global budget of baryons (for $H_0 \geq 50$ km/sec/Mpc) corresponds to a much higher lower bound: $\eta_{10} \geq 1.5$, which is still consistent with the “low- η ” range we identified using the high D results. A possible challenge to the “low- η ” case comes from the analysis of Steigman, Hata & Felten [81] who used observational constraints on the Hubble parameter, the age of the Universe, the “shape” parameter, and the X-ray cluster gas fraction to provide non-BBN constraints on the present density of baryons, finding that $\eta_{10} \geq 5$ may be favored over $\eta_{10} \leq 2$. Even so, a significant low- η , high-D range still survives.

5 Constraints from BBN

Limits on physics beyond the standard model are mostly sensitive to the bounds imposed on the ${}^4\text{He}$ abundance. As described earlier, the ${}^4\text{He}$ abundance is predominantly determined by the neutron-to-proton ratio just prior to nucleosynthesis; this latter is set by the competition between the weak interaction rates and the universal expansion rate. Modulo the occasional free neutron decay, the neutron-to-proton ratio “freezes-out” at a temperature ~ 800 keV. While the

weak interaction rates converting neutrons to protons and vice-versa are “fixed”, there may be room for uncertainty in the expansion rate which depends on the total mass-energy density. For example, the presence of additional neutrino flavors (or of any other particles which would contribute significantly to the total energy density) at the time of nucleosynthesis would increase the total energy density of the Universe, thus increasing the expansion rate, leading to an earlier freeze-out, when the temperature and the n/p ratio are higher. With more neutrons available, more ${}^4\text{He}$ can be synthesized. In the standard model the energy density at a temperature of order 1 MeV is dominated by the contributions from photons, electron-positron pairs and three flavors of light neutrinos. We may compare the total energy density that in photons alone through N which counts the equivalent number of relativistic degrees of freedom.

$$\rho = (N/2)\rho_\gamma \quad (4)$$

In the standard model at $T \sim 1$ MeV, $N_{\text{SM}} = 43/4$, so that we may account for additional degrees of freedom by comparing their contribution to ρ to that of an additional light neutrino species

$$N = N_{\text{SM}} + 7/8\Delta N_\nu \quad (5)$$

For ΔN_ν sufficiently small, the predicted primordial helium abundance scales nearly linearly with ΔN_ν : $\Delta Y \approx 0.013\Delta N_\nu$. Hence, any constraints on Y lead directly to bounds on ΔN_ν [82]. However, it is worth recalling that the constraint is, ultimately, on the ratio of the Hubble parameter (expansion rate) and the weak interaction rate at BBN, so that changes in the weak and/or gravitational coupling constants can be similarly constrained [11, 83]. Here we will restrict our attention to the limits on N_ν and on neutrino masses from BBN. Although likelihood methods have been used to obtain more exact limits on N_ν [84], again here we adopt a simpler, more broad brush approach. Many of the limits on particle properties were recently reviewed in [85].

Given the observational upper bound on Y_{P} of 0.248 and a predicted lower bound of 0.244 (for low-D), there is room for an increase in the BBN-predicted ${}^4\text{He}$ of $\Delta Y = 0.004$. From the scaling of Y with ΔN_ν , we derive an upper limit to ΔN_ν of $\Delta N_\nu < 0.3$. It should be cautioned that this bound is really less stringent than a true “ 2σ ” upper limit, since we have chosen 2σ ranges both in the predicted and the observed deuterium and helium abundances. Even so, for low-D this constraint is already good enough to permit an exclusion of any “new”, light scalars (which would count as $\Delta N_\nu = 0.57$), as well as a fourth neutrino. For high-D we predict a lower bound of $Y = 0.225$ to be compared with the observed upper bound of with $Y = 0.248$, and using the same argument, we derive an upper bound of $\Delta N_\nu < 1.8$.

It should be noted that the limit derived above is not restricted to full strength weak interaction neutrinos. In fact, since we know that there are only three standard neutrinos, the limit is most usefully applied to additional particle degrees of freedom which do not couple to the Z^0 . For very weakly interacting particles which decouple very early, the reduced abundance of these

particles at the time of nucleosynthesis must be taken into account[86]. For a new particle, χ , which decoupled at $T_d > 1$ MeV, conservation of entropy relate the temperature of the χ s to the photon/neutrino temperature (T) at 1 MeV, $((T_\chi/T)^3 = ((43/4N(T_d)))$. Given $g_{B(F)}$ boson (fermion) degrees of freedom,

$$\Delta N_\nu = \frac{8}{7} \sum \frac{g_B}{2} \left(\frac{T_B}{T}\right)^4 + \sum \frac{g_F}{2} \left(\frac{T_F}{T}\right)^4. \quad (6)$$

As an example of the strength of this bound, models with right-handed interactions, and three right-handed neutrinos, can be severely constrained since the right-handed states must have decoupled early enough to ensure that $3(T_{\nu_R}/T_{\nu_L})^4 < \Delta N_\nu$. Using the high D limit to N_ν , three right-handed neutrinos requires $N(T_d) \gtrsim 15$, implying that $T_d > 40$ MeV. In contrast, the low D limit requires that $N(T_d) \gtrsim 60$ so that $T_d > 300$ MeV. If right-handed neutrino interactions are mediated by additional gauge interactions, associated with some scale $M_{Z'}$, and if the right handed cross sections scale as $M_{Z'}^{-4}$, then the decoupling temperature of the right handed interactions is related to $M_{Z'}$ by $(T_{dR}/T_{dL})^3 \propto (M_{Z'}/M_Z)^4$ which, for $T_{dL} \sim 3$ MeV requires $T_{dR} \gtrsim 40(300)$ MeV, the associated mass scale becomes $M_{Z'} \gtrsim 0.6(2.8)$ TeV! Note that this constraint is very sensitive to the BBN limit on N_ν .

Many other constraints on particle properties can be related to the limit on N_ν . For example, neutrinos with MeV masses would also change the early expansion rate, and the effect of such a neutrino can be related to that of an equivalent number of light neutrinos [87, 88, 89, 90]. A toy model which nicely contains ways to both increase and decrease ${}^4\text{He}$ production relative to standard BBN is the case of a massive ν_τ [88]. The two relevant parameters are the ν_τ mass and lifetime. A ν_τ which is stable on BBN timescales (*i.e.*, $\tau_\nu \gtrsim 100$ sec) and has a mass greater than a few MeV will increase Y_P relative to standard BBN. This is because such a neutrino still decouples when it is semi-relativistic and so its number density is comparable to that of a massless neutrino. However, its energy density at the onset of BBN is much greater than that of a massless neutrino since its mass is significantly greater than the temperature. Therefore, weak interactions decouple earlier, increasing the neutron-to-proton ratio at freeze out and thus the amount of ${}^4\text{He}$. For example, a limit of $N_\nu \leq 4$ translates into a mass limit on a relatively stable (on the time-scale of BBN) neutrino of $m_\nu < 0.4$ MeV for a Dirac-mass neutrino and $m_\nu < 0.9$ MeV for a Majorana-mass neutrino [90]. Just the opposite can occur if such a ν_τ decays rapidly compared to BBN timescales. The rapid decays and inverse decays keep the ν_τ s in equilibrium much longer than do the conventional weak interactions so that their number density, along with their energy density, is exponentially suppressed. A typical example is a relative decrease in Y_P of about 0.01 for a ν_τ with a mass of ~ 10 MeV and a lifetime ($\nu_\tau \rightarrow \nu_\mu + \phi$ where ϕ is a Majoron) of 0.1 sec.

6 Conclusions

In this precision era of Cosmology the BBN abundances are predicted with great accuracy in the standard model. The statistical uncertainties in the primordial abundances of the light nuclides inferred from the observational data are also very small. However, there is evidence that the derived abundances may be subject to systematic errors much larger than the statistical errors. This is particularly evident for deuterium where the D/H ratio derived for two, low metallicity, high redshift absorption systems differs by a factor of 5 - 10 from that inferred for a third such system. For ^4He , two determinations of the primordial mass fraction differ from each other by 2 - 3 times the statistical error. Their differences may be traced to differing treatments of the corrections for collisional excitation and ionization and the data sets may be contaminated by some cases of underlying stellar absorption. Although a clear, accurately determined “plateau” is evident in the Li vs. Fe relation for the metal-poor halo stars, the level of the plateau is subject to uncertainties in the metal-poor star temperature scale and atmosphere models. In addition, there may be non-negligible corrections (larger than the statistical uncertainties) due to depletion of surface lithium in these very old stars, as well as enhancement due to post-BBN production. Nonetheless, despite these nagging uncertainties, the agreement between the predictions of standard BBN and the observed abundances is impressive. The standard model passes this key test with flying colors.

Given the dichotomy in the possible primordial abundance of deuterium, we have considered two possibilities. For the “low-D” option, we identify a “high- η ” range (at 95% confidence): $\eta_{10} \approx 4.2 - 6.3$. In this range the predicted abundances of ^3He , ^4He and ^7Li are consistent with the primordial abundances inferred from observations (see Figures 1 - 3). For η in this range the baryon density parameter is restricted to: $\Omega_B h^2 \approx 0.015 - 0.023$ which, for $H_0 = 70$ km/s/Mpc corresponds to: $\Omega_B \approx 0.03 - 0.05$. Using the upper bound to Y_P from the data along with the lower bound to η leads to a “high- η ” bound to the number of “equivalent” light neutrinos: $N_\nu \leq 3.3$. For the “high-D” option a “low- η ” range is identified: $\eta_{10} \approx 1.2 - 2.8$. In this range as well there is overlap between the predicted and observed primordial abundances of ^3He , ^4He and ^7Li . For this “low- η ” range, $\Omega_B h^2 \approx 0.004 - 0.010$ which, for $H_0 = 70$ km/s/Mpc corresponds to: $\Omega_B \approx 0.01 - 0.02$. In this range the upper bound to the number of equivalent light neutrinos is much less restrictive: $N_\nu \leq 4.8$. As a key probe of early Universe Cosmology and of particle physics (standard model as well as beyond the standard model), BBN is alive and well.

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